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Internal Note No. 67-FM-176

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

MSC INTERNAL NOTE NO. 67-FM-176

November 24, 1967

PRELIMINARY EVALUATION OF THE POLYNOMIAL AND INTEGRATED MODES OF THE GENERALIZED ITERATOR FOR LOI TARGETING IN THE RTCC

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(NASA-TM-X-69413) PRELIMINARY EVALUATION OF THE POLYNOMIAL AND INTEGRATED MODES OF THE GENERALIZED ITERATOR FOR LOI TARGETING IN THE RTCC (NASA) 18 p

N74-70504

Unclas
00/99 16196

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PROJECT APOLLO

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By David K. Banner

SUMMARY

A study has been made of targeting the lunar landing mission LOI burns by using the integrated and polynomial modes of the generalized iterator. The results provide a preliminary evaluation of using the generalized iterator for LOI targeting in the RTCC.

Both attainable cases, i.e., the desired nominal variable values that can be attained, and non-attainable cases, i.e., the values can be attained only with the integrated-burn cases, were studied.

The results show that, given the independent variables, the convergence of the iterator becomes more dependent on the independent variables and that the fully optimized mode could be run in about 3 minutes as compared to the polynomial requiring a few seconds. However, being able to pick the cross-product steering constant in the integrated modes allows greater flexibility in picking a solution.

INTRODUCTION

To evaluate using the generalized iteration in the RTCC to target the LOI burn, a study has been made of both the integrated and polynomial burn simulation.

The independent and dependent arrays used are not those that will be used for RTCC LOI targeting since these arrays were not known when the study began. The optimize mode was used differently from its normal use (e.g., in the midcourse processor). Normally this mode is used to drive a variable toward a value that is unattainable (e.g., mass after TEI to a value several hundred pounds above any physically possible solution). In this study, the variable to be optimized was driven to values that are sometimes physically attainable. This use of the optimized mode is expected in the RTCC.

In this study, the desired nominal dependent variable values that could be attained by both the polynomials and the integrated burn simulation are termed attainable cases. Cases in which the nominal values of ϕ_{LLS} and Ψ_{LLS} could be attained only by the integrated burn were referred to as non-attainable cases.

This note assumes the reader is familiar with the iterator; consequently terminology concerning the iterator is not defined. Information about the iterator can be found in references 1 and 2.

SYMBOLS

LOI	lunar orbit insertion
H_{BO}	height of burnout for the LOI burn
λ_{LLS}	longitude of the lunar landing site
ϕ_{LLS}	latitude of the lunar landing site
Ψ_{LLS}	azimuth over the lunar landing site
γ_{LOI}	flight-path angle at start of LOI
$\Delta\Psi_{LOI}$	plane change during LOI
Δt_{1P}	elapsed time from base time to first pass over the lunar landing site
c	cross-product steering constant
T_{IGN}	time of ignition for LOI
θ_N	true anomaly at the node
ΔV_{LOI}	change in velocity required for the LOI maneuver
$\Delta\Psi_N$	change in azimuth at the node (for impulsive maneuvers, same as $\Delta\Psi_{LOI}$)
LPO	lunar parking orbit
RTCC	Real-Time Computer Complex

ANALYSIS

In order to cover the LOI problem as comprehensively as possible, four nominal trajectories were selected as test cases. These nominals have nodes between the approach hyperbola and the lunar parking orbit designed to occur before, at, and after pericynthion. These are described in table I.

LOI circularization guidance, in which the required velocity is defined to be the circularization velocity at the present radius to the spacecraft, was used for the LOI burn. This required velocity lies in a plane defined by the present spacecraft position vector and a target vector.

The study consisted of running both select mode and optimize mode cases on the generalized iterator with the four discrete nominal trajectories (table I). With independent variables of ΔT_{1P}, γ_{LOI}, and $\Delta\Psi_{LOI}$ for the polynominal burn and ΔT_{1P}, θ_N[a], $\Delta\Psi_{LOI}$, c, and T_{IGN} for the integrated burn (tables II and III, respectively), the generalized sequence of events for the study followed this pattern.

First, run each trajectory in the select mode using the following dependent array:

H_{BO}	Class I variable
ϕ_{LLS}	Class I variable
λ_{LLS}	Class I variable
Ψ_{LLS}	Falls out

Second, run the trajectories in the optimize mode using this dependent array:

H_{BO}	Class I
ϕ_{LLS}	Class III (optimized variable)
λ_{LLS}	Class I
Ψ_{LLS}	Class II

---

[a]Note that θ_N and γ_{LOI} both define a nodal position on the approach hyperbola.

This represents a type of "one-dimensioned minimum miss at the site" criteria; i.e., obtain the correct λ_{LLS} and minimize the miss of the ϕ_{LLS}. In addition, the H_{BO} must be obtained. This reflects the current LOI philosophy that the top priority item is to obtain H_{BO}, then minimize the miss at the site. It generally requires fewer corrective maneuvers to obtain the plane of the site in LPO than to correct a dispersed H_{BO}.

Third, change the magnitude of ϕ_{LLS} so that the iterator cannot get the exact ϕ_{LLS} using the polynomial LOI simulation; i.e., optimize ϕ_{LLS}.

Finally, run the trajectories with the finite burn to see how much H_{BO} can be gained by "freeing up" c.

The step sizes for the perturbations of the independent variables, the independent variable weights, and the dependent variable tolerances are shown in tables II and III for the polynomial and integrated burn, respectively.

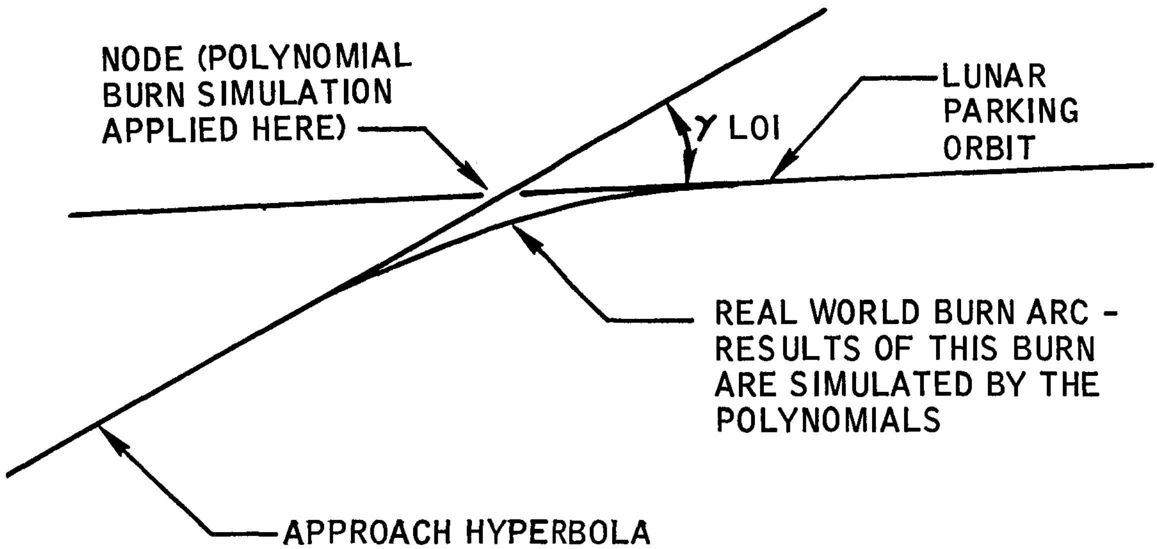
LOI Polynomial Simulation

In the formulation of logic for an LOI subprocessor for the Real-Time Computer Complex (RTCC), one must analyze many possible alternatives. First of all, a decision must be made concerning the type of burn simulation to be utilized in various setups of the targeting logic. The advantages and disadvantages of an integrated burn are readily apparent, in fact it is precisely the computer time involved in this integrated burn that necessitates the using of a conic or a polynomial simulation when feasible.

The LOI polynomial simulation performs the burn impulsively at the node between the LPO and approach hyperbola. (See figure on the following page.) The polynomials provide a Δh, ΔT, and ΔV for the burn. Thus, by knowing the geometry of the approach hyperbola and the desired LPO, it is necessary only to find the nodal position on the approach hyperbola, subtract Δh in altitude (the so-called "height drop") and add ΔT in time to obtain the LPO. The resultant circular parking orbit closely approximates that obtained by integrating the LOI maneuver. However, the polynomials assume a constant value of $c = 1$ for the thrusting maneuver and, thus, a variable c cannot be simulated.

LOI Integrated Burn Simulation

There will exist, in the real-time computation of the LOI maneuver, cases whereby the H_{BO} could not be achieved in the LOI polynomial simulation. Since the polynomials presuppose a value of $c = 1$, it has been hypothesized that by "freeing up" this constant, the correct burnout altitude could be bought at the expense of more LOI ΔV and a higher or lower (than one)



value of c. The purpose of this portion of the study was to ascertain the effect of c in these cases. The implications for real-time applications are apparent; while in the polynomial mode there exists only one solution that will pass over the site with the correct Ψ_{LLS} (because of c = 1), the integrated mode allows a family of solutions. This lends flexibility to real-time planning.

The basic philosophy that permeated the LOI polynomial simulation; i.e., get the H_{BO} and minimize miss at the site, will be observed in the integrated mode.

The Independent Variable Array

The following set of independent variables were utilized to compute the target vector (90° from the node) for LOI: $\Delta T_{1st\ pass}$, θ_N, $\Delta\Psi_N$, c, T_{IGN}. The ΔT_{1P}, first guess was obtained from the summary page of a converged polynomial run; θ_N was taken from the osculating elements at the start of lunar deboost; $\Delta\Psi_N$ was the algebraic difference between Ψ_{BO} and $\Psi_{Start\ LOI}$; c was nominally first guessed as one and T_{IGN} was computed using time at the node and the "back-up equation". θ_N, $\Delta\Psi_N$, and the central angle from the node to the target vector fixed the parking orbit with respect to the approach hyperbola. T_{IGN} was used to control Ψ_{LLS} while c was utilized to obtain the correct H_{BO}.

At first glance the use of both T_{IGN} and θ_N seems to be over-defining the problem; but, as it turns out, both are needed to help the iterator converge on an optimum solution. This implicitly means that by keeping θ_N on as an active variable redefines the target LPO and helps the program work.

RESULTS

The Polynomial Simulation

Several observations were made during the study of the polynomial simulations. It was found that, if the variable to be optimized has too large a weight at the beginning of the optimize mode, the Class I variable (H_{BO}) is driven away from a solution. This problem can be alleviated by the following procedure: either tighten the tolerance on H_{BO} (e.g., to $\pm$0.1 n. mi.) or multiply the internally computed weight on the variable to be optimized (ϕ_{LLS}) by a factor of, say, 0.01. The latter method was chosen for the optimum step size/tolerance/weight set because the 0.1-n. mi. tolerance might cause nonconvergence on trajectories with a true optimum of, say, H_{BO} = 80.247 n. mi. (See nominal case 4 in table IV(a)). However, even with this procedure, the question now arises: Do you lose solutions in the optimize mode through improper weighting techniques? Since the answer appears to be yes, this has far reaching implications for mission planning.

Another minor problem noted in using the programs was that the shutoff criteria in the optimize mode seems inefficient. Its operation is tolerable for preflight analysis; but, for real-time applications, it might not suffice. After a careful study of the typical behavior of the variable XLAMBDA throughout the optimize iterations (fig. 1), it seems apparent that a shutoff criterion to terminate computations after a "plateau" is reached might be feasible. In other words, after approximately eight iterations, the problem is essentially optimized (at least to two significant places); the remainder of the optimize procedure is concerned with small adjustments in each of the dependent variables. This problem was particularly acute for this study since most of the work was done optimizing on conditions the iterator could achieve; therefore, the residual vector upon entering the optimize mode was so small that ϕ_{LLS} became weighted too heavily and H_{BO} was drawn out. The iterator was designed to optimize on conditions it could not attain.

Early in the study it became apparent that γ_{LOI} was a highly significant independent parameter for the LOI maneuver. If this parameter is allowed to move freely in the search procedure, sometimes a postpericynthion solution may be found where no prepericynthion exists; i.e., γ_{LOI} may pass from a negative value through zero to a positive value. Allowing γ_{LOI} to move freely has an undesirable effect; also, this variable will take the place of c in manipulating H_{BO} and/or ϕ_{LLS} in this integrated burn.

Midway in the analysis several factors which influence the attainment or nonattainment of a Class III variable became apparent:

(1) Tolerances on the Class I and Class II variables.

(2) Internally computed weight on the Class III variable.

(3) Weights on the Class II's.

(4) Weights and step sizes on the independent variables.

These statements may seem innocuous at first glance, but they all play a major part in selecting the optimum set of constraints for the LOI problem. It is obvious that, for any given trajectory, you may or may not attain the Class III variable, depending entirely upon the selection of the factors listed above. Therefore, a certain amount of uncertainty will always exist even with a so-called "optimum" set of constraints.

Another interesting fact was uncovered in this study. Through a programing error the trajectory was propagated from H_{BO} to the first pass over the site in the integrated mode; this took approximately 3 minutes per iteration. This has real-time significance; either some calibrated method, i.e., lunar AEG, EMPERT, etc., or a conic propagation must be used for computer time considerations.

Much controversy was aroused due to the comparatively tight tolerances of $\pm 1.0^\circ$ on Ψ_{LLS} as a Class II variable. It was argued, and justifiably so, that no matter where the search procedure started, it would quickly hit a bound, lock, unlock, hit the bound again, etc., thereby hampering attainment of the optimized solution. One way to avoid the problems created by the tight Ψ_{LLS} bounds is to start the case in the optimize mode so that the "begin moving" criteria is never seen. The moral of this story is to either (1) set loose tolerances on Class II variables, or (2) start in the optimize mode where the best possible solution is attained within the restricted bounds. This problem does not occur often, however, and it is thought that the optimum set of constraints listed before will prevent its occurrence in most cases.

The Integrated Burn Simulation

Attention is directed to table IV. For the attainable cases, several items of note become apparent. The prepericynthion burns (cases 1 and 2) are extremely comparable; even such inactive variables as Mass after LM separation and ΔV_{LOI} are close between the integrated and polynomial modes. With case 3 (postpericynthion burn), however, the mass values differ by some 87 lb; but, the actual plane change made when using the integrated burn was 1.2° greater than the polynomial case and c was reduced to 0.8234. This occurred because the integrated simulation locked the azimuth in the -86.0° boundary; thus, it was necessary to change c to obtain the desired end conditions. Why the integrated solution Ψ_{LLS} should be so different from the polynomial Ψ_{LLS} when the other three cases are so close is not now known. However, at this stage in LOI analysis, it is felt that a c of 0.8234 and a 1.2° difference in plane change accounts for the mass difference. Note that this essentially means that the iterator found one of the afore-mentioned "family" of solutions by changing c and using more fuel. Case 4 (a burn essentially at pericynthion) shows reasonable comparison between the integrated and polynomial burns, although not quite as good as cases 1 and 2.

Table IV(b) shows the effect of c much more markedly. Case 1 adjusted on $\Delta\Psi_N$, and c to come closest to the desired end conditions. The iterator converged on a ϕ_{LLS} in the integrated burn mode that was not the desired value. It is assumed at this time that this was caused by weighting and step size problems since there is no physical reason why the desired value should not be obtained in the extra freedom of the integrated burn. The advantages of the integrated burn are more vividly illustrated in case 2. In the polynomial mode, a solution did not exist for this trajectory under the given constraints. However, by manipulating c, the iterator was able to converge on exactly the required ϕ_{LLS}, using 58.6 lb more of fuel. Using only the polynomial burn the desired ϕ_{LLS} would have been missed by better than 0.6°, which would undoubtedly require a maneuver LPO. Therefore, the 58.6 lb of fuel saved an LPO maneuver in this case.

The results tabulated under case 4 show that sometimes even the extra degree of freedom of the integrated burn is of no practial help. This case with the integrated burn was not converged; it was terminated on an iteration count. The case was not rerun since the results then illustrated the point and running the case until it converged would take more computer time than the results would be worth. Because of the small plane change (less than 1°) the node between the approach hyperbola and the LPO associated with the maximum allowable Ψ_{LLS} shifted drastically as ϕ_{LLS} was changed. Consequently, so much altitude drop would be required at the node that the fuel used would be unacceptable. Notice also how uneconomical large values of c are. This is a case where a two-burn LOI is most economical. The same sort of thing was tried in case 3. The ϕ_{LLS} was increased to 1.627° as the desired value. The polynomial simulation was only able to reach 1.086° whereas the integrated burn was able to attain the desired value. However, the mass difference was so great that it could not be explained. Consequently, these results were not included in the tabulated data. An attempt is being made to explain this discrepancy.

CONCLUDING REMARKS

Several observations were noted during this study. It was found that in the integrated mode, convergence became much more dependent on the step sizes given the independent variables (especially for case 2, a high $\Delta\Psi$ case and case 6, an "at" pericynthion burn). The set of weights, tolerances, and step sizes shown in table III do not, therefore, represent a "true" optimum set as does table II for the polynomials. More refinement work needs to be done in this area.

It was found that a fully optimized integrated burn could generally be run for somewhat less than 3 minutes on the 1108 while the polynomials would run in a few seconds. However, the integrated mode offers the unique advantage of having c to use as a means of picking a member of the family of solutions at different places on the approach hyperbola at the expense of more ΔV.

Note that the "optimum" set of constraints mentioned above could be improved by multiplying the internally computed weight on ϕ_{LLS} by a scaling factor to insure that solutions are not driven out in the optimize mode.

TABLE I.- DESCRIPTION OF NOMINAL LOI'S

Case	Date	Time, hr G.m.t.	Description
1	October 26, 1968	3.75	prepericynthion; approximately 1° plane change
2	February 4, 1968	20.31	prepericynthion; large plane change
3	February 4, 1968	12.94	postpericynthion; large plane change
4	December 1, 1968	9.98	at pericynthion; coplanar

TABLE II.- OPTIMUM STEP SIZES, TOLERANCES, AND WEIGHTS

FOR THE POLYNOMIAL BURN[a]

Variable	Octal step size	Tolerances	Weights
Independent variables			
$\Delta T_{1st\ pass}$	ϕ17574	--	0.001
$\Delta\Psi_{LOI}$	ϕ17564	--	0.1
γ_{LOI}	ϕ17554	--	4.0
Dependent variables			
H_{BO}	--	$\pm$0.5 n. mi.	--
ϕ_{LLS}	--	--	--
λ_{LLS}	--	$\pm$0.01 deg	--
Ψ_{LLS}	--	$\pm$1.0 deg	1.0

[a]Used a weight factor of 0.01 on the variable to be optimized (ϕ_{LLS})

TABLE III.- OPTIMUM STEP SIZES, TOLERANCES, AND WEIGHTS

FOR THE INTEGRATED BURN

Variable	Octal step size	Tolerances	Weights
Independent variables			
$\Delta T_{1st\ pass}$	ϕ17554	--	0.001
$\Delta \Psi_N$	ϕ17604	--	1.0
θ_N	ϕ17604	--	1.0
c	ϕ17624	--	0.015625
T_{IGN}	ϕ17604	--	0.001
Dependent variables			
H_{BO}	--	$\pm$0.5 n. mi.	--
ϕ_{LLS}	--	--	--
λ_{LLS}	--	$\pm$0.01 deg	--
Ψ_{LLS}	--	$\pm$1.0 deg	1.0

TABLE IV.- COMPARISON OF THE RESULT OBTAINED BY THE POLYNOMIAL CURVE FIT AND INTEGRATION THROUGH THE GUIDANCE EQUATIONS TO THE DESIRED NOMINAL VALUES FOR THE LOI BURN

(a) Attainable Cases

Case	H_{BO}, n.mi.	ϕ_{LLS}, deg	λ_{LLS}, deg	ψ_{LLS}, deg	Mass after LOI, lb	ΔMass Polyn-Integ	Δt_{1P}, hours	θ_N, deg	γ_{LOI}, deg	$\Delta\Psi_N$, deg	$\Delta\Psi_N$ actual	c, n.d.	T_{IGN}, hours from G.m.t.
Nominal 1, Polynomial	80.000	2.751	34.000	-85.166	67693.7345	--	19.227	-7.791	-4.685	.165	--	1.0000	3.719
Desired	80.000	2.751	34.000	-84.000	--	--	--	--	--	--	--	--	--
Nominal 1, Integrated	80.000	2.751	34.000	-85.165	67706.2644	-12.5299	19.1737	-7.990	--	.165	.17	1.0000	3.664
Nominal 2, Polynomial	80.000	.333	24.833	-87.224	66284.8633	--	19.229	-7.655	-4.558	11.491	--	1.0000	20.279
Desired	80.000	.333	24.833	-87.000	--	--	--	--	--	--	--	--	--
Nominal 2, Integrated	80.000	.333	24.833	-87.210	66293.9702	-9.1069	19.170	-7.654	--	11.478	11.47	1.0000	20.221
Nominal 3, Polynomial	80.000	.327	24.832	-86.079	64186.4372	--	19.153	14.483	8.862	12.747	--	1.0000	12.993
Desired	80.000	.327	24.832	-87.0	--	--	--	--	--	--	--	--	--
Nominal 3, Integrated	80.000	.327	24.832	-86.000	64119.9769	66.4603	19.906	14.461	--	12.687	13.90	.8234	12.927
Nominal 4, Polynomial	80.243	1.670	-41.670	-89.341	68910.1664	--	19.595	.666	.392	.903	--	1.0000	9.978
Desired	80.000	1.670	-41.660	-89.289	--	--	--	--	--	--	--	--	--
Nominal 4, Integrated	80.000	1.670	-41.670	-89.343	68880.4122	29.7542	19.546	.666	--	.904	.91	1.0437	9.925

TABLE IV.- COMPARISON OF THE RESULT OBTAINED BY THE POLYNOMIAL CURVE FIT AND INTEGRATION THROUGH THE GUIDANCE EQUATIONS TO THE DESIRED NOMINAL VALUES FOR THE LOI - Concluded

(b) Non-attainable Cases

Case	H_{BO}, n.mi.	ϕ_{LLS}, deg	λ_{LLS}, deg	Ψ_{LLS}, deg	Mass after LOI, lb	ΔMass Polyn-Integ	Δt_{1P}, hours	θ_N, deg	γ_{LOI}, deg	$\Delta\Psi_N$, deg	$\Delta\Psi_N$ actual	c, n.d.	T_{IGN}, hours from G.m.t.
Nominal 1, Polynomial	79.971	3.184	34.000	-86.001	67678.1840	--	19.227	-7.764	-4.669	1.107	--	1.0000	3.719
Desired	80.000	3.751	33.990	-85.0	--	--	--	--	--	--	--	--	--
Nominal 1, Integrated	80.892	3.576	34.000	-86.024	67725.1468	46.9628	19.094	-7.756	--	1.305	1.35	.6375	3.715
Nominal 2, Polynomial	79.920	-.295	24.833	-86.000	66682.5518	--	19.225	-7.596	-4.523	10.116	--	1.0000	20.280
Desired	80.000	.333	24.833	-85.000	--	--	--	--	--	--	--	--	--
Nominal 2, Integrated	80.000	.333	24.833	-85.975	66741.1233	58.5715	19.155	-7.125	--	10.385	10.40	.5852	20.233
Nominal 4, Polynomial	80.255	2.484	-41.670	-88.289	68920.3963	--	19.595	.608	.358	-.428	--	1.0000	9.978
Desired	80.000	5.670	-41.670	-89.289	--	--	--	--	--	--	--	--	--
Nominal 4, Integrated	80.123	2.656	-41.678	-88.267	67727.6816	1192.7147	19.611	-1.377	--	-.955	-.56	3.451	9.880

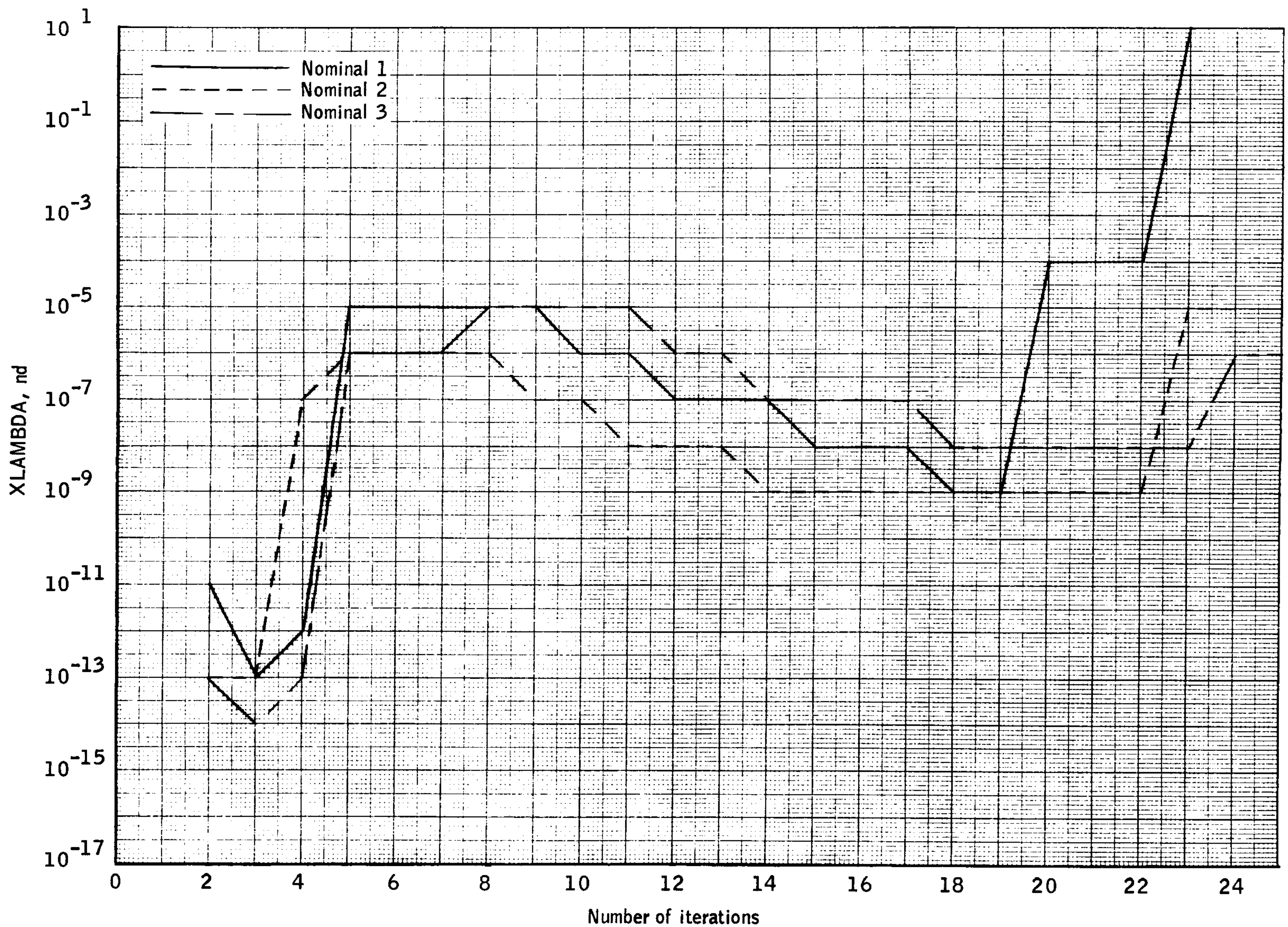


Figure 1.- Behavior of the variable XLAMBDA through succeeding iterations in the polynomial simulation of the attainable nominal cases 1, 2, and 3.

REFERENCES

1. Moore, William E.: The Generalized Forward Iterator. MSC Internal Note No. 66-FM-55, June 15, 1966.

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